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IDA MEMORANDUM REPORT M-122

REPORT ON THE IST/IDA GAMMA-RAY LASER WORKSHOP 21-22 MAY 1985

Bohdan Balko
Leslie Cohen
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November 1985

Prepared for
Strategic Defense Initiative Organization
Innovative Science and Technology Office
James Ionson, *Director*

INSTITUTE FOR DEFENSE ANALYSES
1801 N. Beauregard Street, Alexandria, Virginia 22311

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An historical perspective of the gamma-ray laser effect is presented, beginning with the 1957 discovery of the Mössbauer Effect. A retrospective of the workshop is given, including the principal research workers and laboratories involved. The five principal concepts that emerged and the critical issues attached to each concept are discussed. The conclusions reached as a result of the workshop and the recommendations of the IDA staff for future directions are also presented.

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PREFACE

The Director of Innovative Science and Technology (IST) of the Strategic Defense Initiative Organization (SDIO) had targeted the gamma-ray laser as a potentially important candidate for his program. Consequently, he requested that IDA examine the field and report back on its current status. The initial approach was to convene a two-day workshop at IDA to which all known gamma-ray laser scientists and workers in supporting fields were invited. The purpose was to evaluate the various gamma-ray laser concepts and to identify critical issues which required further work. The workshop program and the participants are listed in the appendix.

This document has not been subjected to an IDA review.

An outgrowth of this workshop was the identification of possible civilian and military applications which are reported separately (IDA Memorandum Report M-141).

I. INTRODUCTION

Gamma rays have many important applications because of their short wavelengths, relatively high penetrating power, and their ability to ionize atoms and molecules. Gamma-ray lasers, or grasers which would provide intense, controllable and directable coherent sources of such radiation--in which phase as well as intensity have significance--would have a revolutionary impact on most fields where both gamma-rays and x-rays are used already or where extensions into this frequency range are desirable. Possible civilian and military applications of such devices are discussed in a companion document (IDA Memorandum Report M-141).

In the spirit of the Innovative Science and Technology Directorate's search for new and innovative methods for generating and controlling the delivery of energy, a workshop was held at the Institute for Defense Analyses (IDA) on May 21 and 22 to evaluate the various gamma-ray laser concepts and identify the critical issues.

The major goals of the IST gamma-ray laser workshop were:

(1) to assemble the major researchers in the field as well as researchers who are representative of supporting technologies,

(2) to identify the strong and weak points of the known gamma-ray lasing schemes,

(3) to identify the role of supporting technologies and their current level of sophistication,

(4) to discuss theoretical concepts which need further study,

(5) to emphasize the need for definitive proof-of-method experiments.

II. HISTORICAL PERSPECTIVE

Optical and x-ray lasers utilize resonant electromagnetic transitions between electronic levels. Gamma-ray lasers, which would use stimulated coherent or cooperative emissions resulting from resonant electromagnetic transitions between nuclear levels, were not thought to be possible in a practical sense until the discovery of the Mössbauer Effect in 1957. Although resonant absorption between levels is commonly observed in the case of atomic transitions, the gamma rays emitted in nuclear transitions are generally very energetic and well-defined, so that recoil of the nuclei prevents resonance between them. Thus, not only is stimulated emission hindered but even ordinary absorption is difficult to observe.

In his important discovery, Mössbauer found that under special conditions nuclear recoil does not occur and resonance between the emission and absorption of gamma-rays is restored. Soon after this discovery, proposals for applying this effect in the development of a gamma-ray laser began to appear in technical journals. Over 100 papers from researchers in the Soviet Union alone were published in the 20-year period after the discovery of the Mössbauer effect. Soviet researchers became the leaders in this effort in the early sixties.

Numerous difficult problems were encountered as research in the area of gamma-ray lasers progressed. In the past, nuclear lasing appeared at best very difficult to achieve, and suspicions arose in the community that it might not be possible. However, advances in experimental and theoretical work indicate that major problems may be overcome and that lasing between nuclear levels may be possible in the future. These problems

and the innovative solutions that were presented at the workshop are discussed in Section IV.

The basic physical concept of a gamma-ray laser is inherently no different from the concept of an optical laser. Nonetheless, the specific requirements for achieving nuclear lasing have thus far been unobtainable in any proposed gamma-ray lasing schemes. Thus, although a number of researchers have investigated the problems associated with gamma-ray lasers, the conclusions appeared only to highlight the seemingly insurmountable hurdles to gamma-ray lasing. Many of the preliminary calculations and further historical developments are well summarized in a review article.*

With the advent of the challenging goals of the Strategic Defense Initiative, the gamma-ray laser became a key innovative concept worthy of careful and open consideration by the Director of the Innovative Science and Technology Office of the SDIO. Thus, on May 21 and May 22 a diverse group of scientists was assembled by IDA to discuss the future directions for research into gamma-ray lasers.

*Baldwin, G.C., J.C. Solem, and V.I. Gol'danskii, Rev. Mod. Phys. 53(4), 687-744, 1981.

III. WORKSHOP RETROSPECTIVE

The Gamma-Ray Laser Workshop brought together more than 30 participants comprising the following groups:

(1) Prime workers in the field of gamma-ray lasers
(2) Skilled workers in essential, supporting technologies
(3) Invited critics and scientific program administrators

The workshop revealed that, basically, there were three groups in the United States working on gamma-ray lasers. The largest, led by George Baldwin at Los Alamos National Laboratory (LANL), has experimental physicists and chemists, theorists, and outside consultants working on the problem. The work has been ongoing for many years and has recently been emphasizing two-stage excitation, laser isomer separation to provide isomeric samples, theoretical studies of nuclear interlevel transfer driven by electronic transitions, and theoretical and data base searches for candidate nuclei. The second group is led by Carl Collins at the University of Texas (Dallas). This group is working on the coherent and incoherent excitation of long-lived isomeric states to shorter-lived lasing states. Collins has recently established a collaboration with a plasma physics group at the University of Rochester to study x-ray flash sources for incoherent excitation. A third group, led by Frank Dietrich, was initiated this year at Lawrence Livermore National Laboratory (LLNL), and is supported by one experimentalist and one theorist. This group will be involved in high-resolution nuclear spectroscopy, theoretical studies, and data base searches with the goal of finding laser candidates. In addition to the three

groups listed above, the IDA staff members conducting the workshop have themselves been working on pumping schemes involving narrowing of widths of long-lived isomeric transition and the use of techniques not requiring recoilless transitions.

There are many Mössbauer-effect scientists in the country and many x-ray physicists working on diffraction and scattering phenomena. They were represented at the meeting; their knowledge and skills will be important in building the actual gamma-ray lasers. Several nuclear experimentalists and theorists were in attendance. It was stated that of the few nuclear facilities capable of doing high-resolution spectroscopy, most were located abroad. Updating equipment at one facility at least may be necessary. New gamma-ray detectors of high resolution may become important.

Clearly emerging from the workshop was the observation that, if a gamma-ray laser is ever developed, it will be the result of a multi-faceted, multi-disciplinary task of large proportions. No specific nuclide, lattice, or specific pumping scheme has been identified. Several schemes have been suggested, each with its concomitant difficulties.

After the workshop, there was much concern that the task that looms ahead will require a great deal of work, most of it to be done in universities and national laboratories. Since many new people would be brought in, especially young faculty members and graduate students, it was considered essential, at this stage, that all aspects of the work remain unclassified. In addition, participants became more strongly aware of the need to submit white papers if they were to remain part of the ISTO effort. As a result of the workshop, a number of participants began to form more collaborative groups. At the end of the workshop, for example, S.S. Hanna of Stanford suggested that, with the new generation of nuclear accelerators and the best detectors, a high-precision study of the spectroscopic structure of candidate nuclides could be undertaken with a high

probability of not missing any levels. The Rochester attendees took this suggestion back to Harry Gove, Professor of Nuclear Physics at their university; the result was that a collaborative proposal has been submitted by the two universities. This liaison would bring 8 to 10 new people into the arena, most of them young faculty members and students. F. Dietrich of LLNL also suggested that a new type of detector employing Josephson junctions, could measure gamma-ray energies to about 30 eV instead of just under 1 keV, as current detectors do. This detector could be used to explore regions of excitation close to isomeric states to find the "missing levels" that were discussed at the workshop. P. Boolchand (University of Cincinnati), B. Post (Polytechnic University of N.Y.), and G. Trammell (Rice University) are suggesting aspects of their work more along the lines of structuring graser crystals utilizing Mössbauer, Borrmann, and Kossel effects. IDA staff members B. Balko, L. Cohen, and F. Hartmann will continue their studies of nuclear magnetic resonance (NMR) line narrowing and overall system concepts, and their investigations of innovative schemes.

There was a consensus among the participants that there is a need for a central nuclear data base specialized for gamma-ray laser studies. IDA consultant A. Artna-Cohen has been working through the Oak Ridge National Laboratory (ORNL) Nuclear Data Group seeking nuclear isomeric data. Others have been using the open literature, such as the 1978 compilation of Lederer and Shirley.

IV. GAMMA-RAY LASER CONCEPTS AND CRITICAL ISSUES

Five gamma-ray laser concepts were presented at the workshop. All were based on the use of long-lived isomeric nuclear levels to store energy. The basic differences between these concepts are contained in the mechanisms proposed to release the stored energy. The concepts, in order of their presentation at the workshop, are as follows:

(1) upconversion by optical or x-ray photons

(2) preparation of dressed states of nuclei

(3) line narrowing of isomeric transition widths by radio frequency (RF) pulses

(4) nuclear interlevel transfer by electronic transitions

(5) stimulation of "transition with recoil" using laser cooling

All except the fifth concept are based on the recoilless or Mössbauer transitions.

The possible use of long-lived isomeric states (lifetimes > 1 sec) for gamma-ray laser development has attracted significant attention because of:

(1) the reduced requirement on pumping power for the inversion (a function of the long pumping time),

(2) the possibility of storing energy for a long time (on the order of the lifetime) in the inverted, isomeric state, and

(3) the possibility of delayed, externally controlled energy release.

Currently, the most promising concepts for a gamma-ray laser appear to be those involving recoilless transitions. The

major problem with the direct use of long-lived isomeric transitions in gamma-ray laser development is inhomogeneous broadening of the nuclear gamma-ray stimulation cross-section. This broadening is due to slightly different environments at different nuclear sites in the host material. Although this broadening has been observed with the usual Mössbauer isotopes, it is particularly devastating to the resonance phenomena involving the ultra-narrow natural linewidths associated with long-lived isomeric transitions.

Approaches to the solution of the line-broadening problem were discussed at the workshop for each of the four "recoilless" gamma-ray concepts. The first two--those involving upconversion and the preparation of dressed nuclear states--use additional high-flux radiation to promote the system to a nearby shorter-lived nuclear state where inhomogeneous line-broadening plays far less of a role. In the third concept--as its description implies--external electromagnetic fields are used to suppress the nuclear spin interactions, a major contributor to the inhomogeneous broadening, thereby restoring resonance and thus promoting stimulated emission. The fourth concept uses optical stimulation of electronic levels to promote nuclear inter-level transfer to a lasing transition.

In all cases, the first step is to prepare a long-lived nuclear state (which detailed considerations require to be on the order of 10 to 100 keV above a lower-lying state) through neutron capture or some other nuclear reaction. In the line-narrowing scheme, suppression of inhomogeneous broadening is achieved by pulsed RF techniques. These techniques are used to restore resonance between nuclei and thus stimulate photon emission. Such RF techniques are being used routinely in high-resolution NMR work but have not yet been applied to line-narrowing in Mössbauer isotopes.

The other techniques use a second, intense, shorter-wavelength pulse to promote the nucleus from the initial long-lived

inhomogeneously broadened level to another near-lying, short-lived state. This new state could be either naturally occurring and accessible by optical or x-ray pulses or a "dressed state" resulting from intense coherent excitation by longer-wavelength electromagnetic radiation (such as RF, optical, or x-ray photons). The required nearby states have not been observed experimentally and thus require further study. The promotion of nuclear interlevel transfer through coupled electronic transitions has been initially examined theoretically but has not yet been observed experimentally.

A notable departure from the general theme of the workshop, i.e., using Mössbauer isomeric transitions, is the last concept on the list which proposes the use of non-Mössbauer transitions. The recoil technique, like the first two, requires the pumping of an isomer by an x-ray source (or a laser) to the upper level of a lasing pair separated by about 10 to 20 keV of energy. The lasing frequency corresponds to (E/h), where E is the transition energy reduced by the recoil energy due to emission. The lasing condition is established by reducing the speeds of all the atoms to a value as close to zero as possible in a time short compared to the lifetime of the lasing level.

The critical issues specific to the implementation of each concept are as follows:

(1) Upconversion by optical or x-ray photons

- existence of nuclear levels within optical or x-ray energies of the isomeric level (missing nuclear data)
- availability of pumping power to achieve inversion of isomeric nuclei
- preparation of host crystals, including isomeric nuclei

(2) Preparation of dressed states

- existence of nuclear levels within $n\hbar\omega$ of a known isomer (ω = frequency of coherent radiation source)

- preparation of dressed states with coherent radiation
- preparation of host crystal, including isomeric nuclei

(3) <u>Line narrowing of isomeric transition widths by RF pulses</u>
- existence of long-lived or stable isotopes for manufacturing isomers
- suppression of inhomogeneous broadening in Mössbauer nuclei by RF pulses
- preparation of pure, defect-free host crystals with substitutionally implanted isomers

(4) <u>Nuclear interlevel transfer by electronic transitions</u>
- proposed mechanisms and measurements of associated rates
- existence of suitable nuclear levels compatible with associated electronic pumping transitions
- suitable laser pumping sources

(5) <u>Stimulation of "transition with recoil" using laser cooling</u>
- producing an atomic or molecular gas containing the nuclear isomer of interest
- finding a pump to make the transition from isomer to lasing state
- finding a tunable laser whose frequency corresponds to a Doppler broadened atomic or molecular transition suitable for cooling
- achieving cooling for a gas sample of density $n > 10^{13}$ atoms/ml in a time short compared to the lasing nuclear lifetime

There are other critical issues associated with population inversion, energy release, and transport of radiation out of the medium--all of which are common to the first four concepts. In

particular, the use of the Borrmann effect for promoting selected transitions and reducing the linear extinction coefficient may be essential to all the concepts. Furthermore, the preparation of an active medium containing the required isotope in a structurally suitable condition (with a high recoilless fraction and other desirable properties which do not appreciably deteriorate during lasing) is essential to the first four concepts. These problems must ultimately be addressed in a complete systems approach to the development of the laser.

V. RECOMMENDATIONS - PROGRAM DIRECTIONS

The recommendations which follow are based on a current view of a gamma-ray laser system--a cylindrical rod of small dimensions, perhaps centimeters in length and microns in diameter. It is either a pure isomeric crystal or a host crystal having some fraction of the nuclei replaced by isomeric nuclides. The crystal must be so formed that Borrmann channeling takes place in a direction parallel to the cylindrical axis and that a high percentage of emissions are recoilless. If the isomeric state is the upper level of the lasing pair, the level must be quickly narrowed by NMR techniques; if it is not, the embedded isomer must be amenable to pumping with x-ray or laser radiation to the nearby lasing level. The stimulated or even "superradiant" radiation will then exit the ends of the rods before the rod is destroyed.

To succeed in achieving the IST goal of a gamma-ray laser, it is recommended that the Director encourage:

(1) the establishment of a usable nuclear data base with concomitant theoretical work to seek out the most likely candidate nuclides for all of the schemes

(2) the performing of high resolution nuclear spectroscopic studies of likely nuclear candidates to include the measurements of excitation energies, branching ratios, internal conversion coefficients, and reaction cross sections for isomer production

(3) the undertaking of experimental studies to synthesize, pure and implanted crystals with acicular geometry to study Mössbauer and Borrmann effects

(4) manufacturing experimental quantities of candidate isomers using both nuclear reaction and laser isomer separation techniques

(5) performing a basic experiment to demonstrate the stimulated emission of nuclear radiation

(6) the performing of a careful Mössbauer scattering experiment to verify the existence of the sidebands that Collins claims to see as well as the undertaking of a concomitant theoretical study of nuclear aspects of "dressed state" description of the coherent pumping scheme

(7) the performing of NMR line-narrowing experiments on long-lived isomers to confirm the technique and to lay to rest the disagreement perpetuated at the workshop, namely, that the time to narrow is at least the order of the natural lifetime

(8) performing preliminary experiments on all major and innovative pumping schemes *until a specific one* clearly emerges as the best

(9) seeking out ideal coherent and incoherent radiation pumping sources

(10) performing theoretical studies on the kinetics and evolution of gamma-ray laser pulses

(11) maintaining an advisory group to stay in touch with the above work, monitor research abroad, seek innovative solutions, and initiate work on relevant problems not being addressed

(12) the publishing of a newsletter to keep IST and the gamma-ray laser community informed of activities and progress.

VI. CONCLUSIONS

As a result of the workshop, discussions with individual investigators, and additional analyses by IDA staff, the following conclusions were reached regarding the gamma-ray laser development effort:

(1) There is no single concept that is so promising that it should be pursued to the exclusion of the others presented at the workshop.

(2) An intense effort should be made in Nuclear Data Base development and search for isotope candidates. There are no outstanding candidates at present. Theory does not rule out their existence and even suggests the directions in which searches should be concentrated.

(3) In addition to the development of pumping and inversion schemes, studies involving photon transport (gamma-ray optics) and pulse evolution must be supported.

(4) System studies should be undertaken for each promising concept; these should include all the parameters of the problem and their interdependence. Thus, crystal preparation, pumping, heating during pumping, and lasing and its effect on the crystal, should be included in the analysis.

(5) There was a consensus among workshop attendees that the gamma-ray laser development effort, at least for the present, should remain unclassified. This is important to the free exchange of ideas and the need for the participation of the university community, which otherwise would be excluded.

APPENDIX A

PROGRAM FOR IDA GAMMA-RAY LASER WORKSHOP

TUESDAY, MAY 21, 1985

MORNING - 8:30 a.m.	WELCOME: Director (IDA) INTRODUCTION: L. Cohen (IDA) PROGRAM AND ADMINISTRATIVE DETAILS: B. Balko (IDA)	

SESSION A: BASICS - Chairman - B. Balko (IDA)

9:00 a.m.	Graser Concepts	- G. Baldwin (LANL)
	Coffee Break (10:00 a.m. to 10:15 a.m.)	
10:15 a.m.	Dynamic Theory of Mössbauer Optics	- G.T. Trammell (Rice U.)
11:15 a.m.	Mössbauer Crystals	- P. Boolchand (U. of Cincinnati)
12:00 noon	Anomalous Absorption of X-rays in Crystals	- B. Post (Polytechnic Institute of NY)
	Working Lunch (12:45 p.m. to 1:30 p.m.)	

AFTERNOON - SESSION B: PUMPING SCHEMES - Chairman - J. Ionson (SDI/IST)

1:30 p.m.	Coherent and Incoherent Upconversion	- C. Collins (U. of Texas)
2:30 p.m.	One-Step and Two-Step Pumping	- G. Baldwin (LANL)
3:30 p.m.	Long Lifetime Gamma-ray Laser	- B. Balko (IDA)
4:10 p.m.	Nuclear Interlevel Transfer Driven by Electronic Transitions	- J. Solem (LANL)

4:50 p.m.	Duguay's Recoil Laser	- L. Cohen (IDA)
5:15 p.m.	First Day Windup	

Group Dinner: 7:30 p.m.

WEDNESDAY, MAY 22, 1985

MORNING - SESSION C: CRITICAL AREAS - Chairman - H. Pilloff (ONR)

8:30 a.m.	Superradiance, Pulse Evolution	- M. Feld (MIT)
9:30 a.m.	NMR and Line Narrowing	- W.K. Rhim (CalTech)

Coffee Break (10:30 a.m. to 10:45 a.m.)

10:45 a.m.	Dressed States	- K. Brueckner (UCSD, La Jolla Institute)
11:30 a.m.	A Search for Candidate Levels	- D. Strottman (LANL)

Working Lunch (12:15 p.m. to 1:00 p.m.)

AFTERNOON - SESSION D: ADDENDA, COMMENTS, WINDUP - Chairman - K. Brueckner (UCSD, La Jolla Institute)

1:00 p.m.	Nuclear Structure	- F.S. Dietrich
1:30 p.m.	Progress in Incoherent Pumping Schemes	- B. Yaakobi, S. Letzring (U. of Rochester)
2:15 p.m.	Unsolicited Comments from Observers	
3:00 p.m.	Free for All - Directed Questions	
3:45 p.m.	Workshop Windup	- J. Ionson (SDI/IST)

APPENDIX B

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